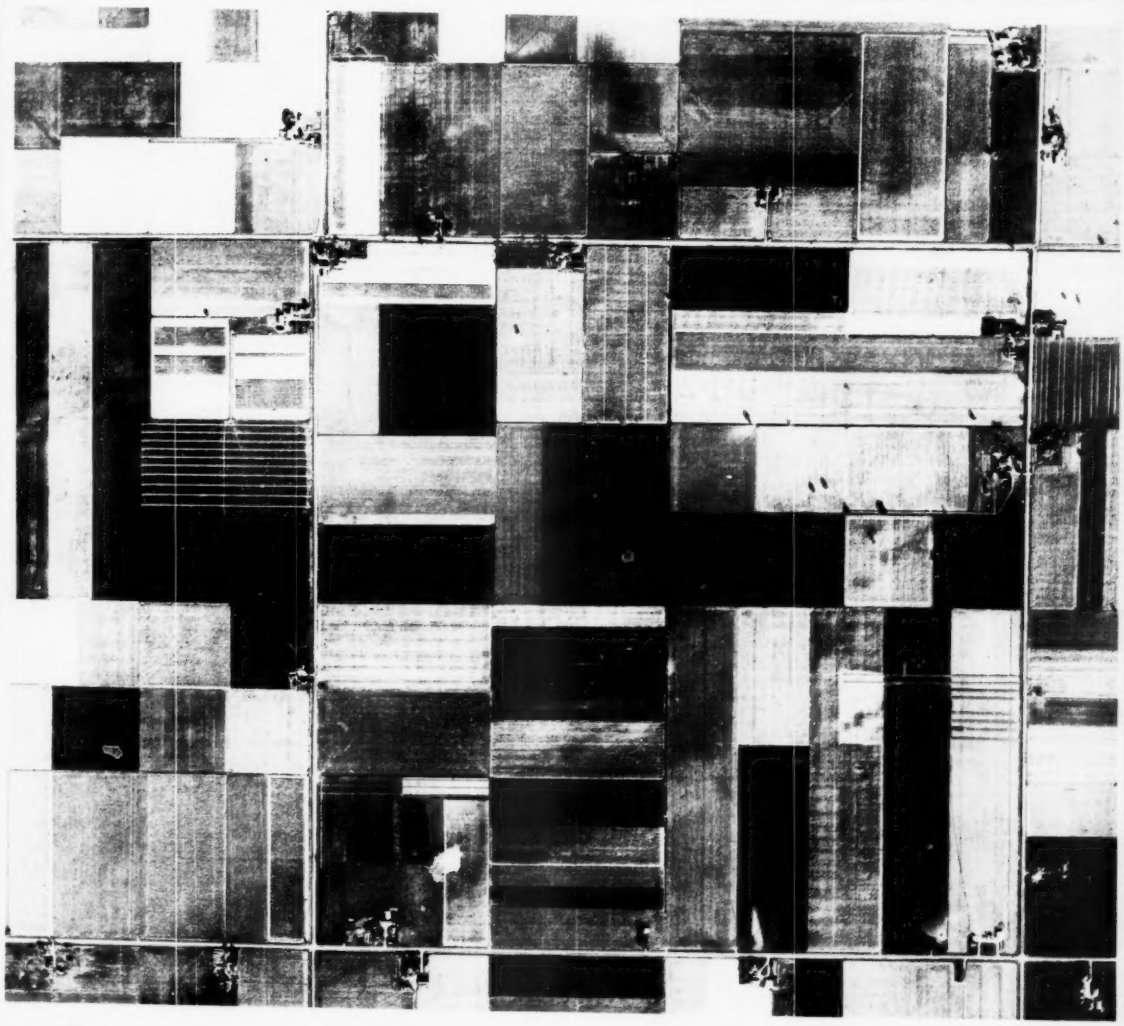
RAYTHEON

ELECTRONIC PROGRESS

March
April 1959



A Photogrammetric Range

In this issue: **SHOCK TESTING**

ELECTRONIC PROGRESS

Volume III March-April 1959 Number 5

RAYTHEON

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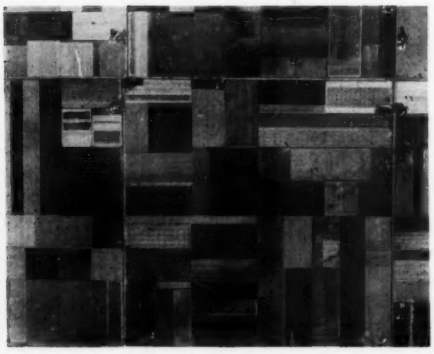
THE COVER



On the cover is an aerial view of the photogrammetric range at McClure, Ohio. This range is used by Raytheon in a special application of photogrammetric technique to check the accuracy of Doppler Navigators.

Calendar

Engineering Seminars

Seminars will be held weekly on Tuesdays at 5:20 P.M. at the Wayland Laboratory cafeteria. Security clearance will be required as indicated on the schedule. Personnel who do not hold picture badges should consult their security officers for attendance arrangements.

"The Oxide Cathode" **F. Hill, Receiving Tube Division**	**Mar. 10**	**Unclassified**
"Raytheon's Standards Engineering Program" **C. W. Watt, Office of the Vice President, Engineering and Research**	**Mar. 17**	**Unclassified**
"Microwave Tubes — Present and Future" **C. L. Calosi, Vice President and Chief Engineer, Microwave and Power Tube Division**	**Mar. 24**	**CONFIDENTIAL**
"Undersea Warfare" **Vice Admiral Charles B. Momsen, USN (Ret), Consultant to Raytheon**	**Mar. 31**	**CONFIDENTIAL**

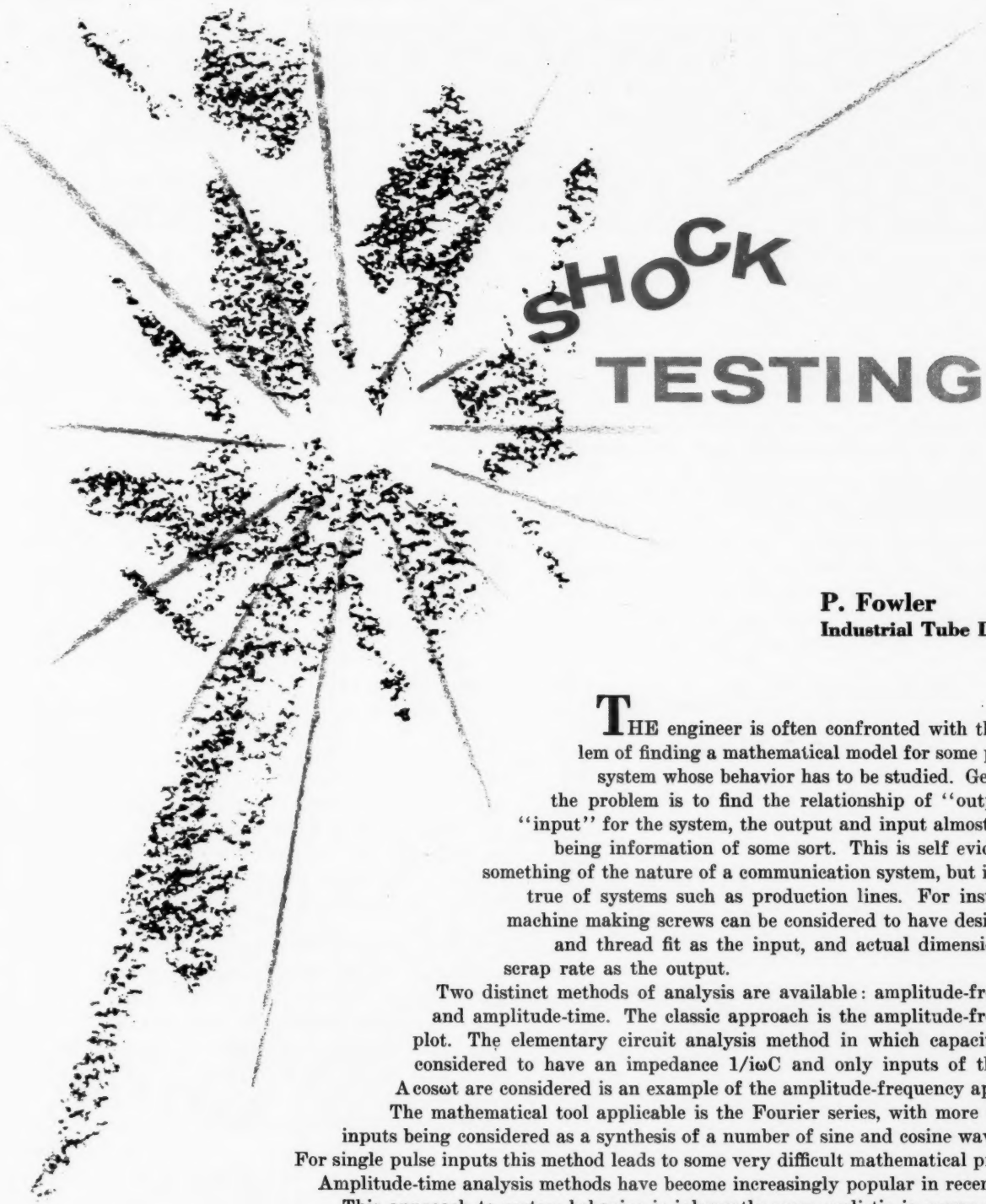
Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

Name	*Field of Invention*
J. Francis Ahearn	Insulator Conductor
Raymond Blanchard	Turbine Bucket Generator
Vito Scandale	
Gerald Brule	Induction Soldering
Leonard Porter	
W. Caithness	New Cathode Material
R. P. Tuinila	
Peter Fowler	Vibrator Coil-Former
Harry Letaw, Jr.	False Alarm Detector
Alvin Luftman	Dynamic Gettering
Carleton Sawyer	
Ralph Mondano	Reflectors Utilizing Shim Stock
Marcel Mussard	Cyclic Decoder
Stanislaw Schroter	Insulating Coating
Burton Smith	Glass Dome Magnetron
Paul Stutsman	Cold Cathode Visual Indicator

Contents

Shock Testing	***P. Fowler***	**1**
Photogrammetric Measurements	***G. Cooper***	**6**
Standards	***C. W. Watt***	**10**
Formation of Silicon Carbide Crystallites	***A. H. Smith***	**14**
Rhenium: A Dark Horse	***P. Levesque***	**18**
Air Force TPPD's		**21**



SHOCK TESTING

P. Fowler
Industrial Tube Division

THE engineer is often confronted with the problem of finding a mathematical model for some physical system whose behavior has to be studied. Generally, the problem is to find the relationship of "output" to "input" for the system, the output and input almost always being information of some sort. This is self evident for something of the nature of a communication system, but it is also true of systems such as production lines. For instance, a machine making screws can be considered to have desired size and thread fit as the input, and actual dimensions and scrap rate as the output.

Two distinct methods of analysis are available: amplitude-frequency and amplitude-time. The classic approach is the amplitude-frequency plot. The elementary circuit analysis method in which capacitors are considered to have an impedance $1/i\omega C$ and only inputs of the form $A\cos\omega t$ are considered is an example of the amplitude-frequency approach. The mathematical tool applicable is the Fourier series, with more realistic inputs being considered as a synthesis of a number of sine and cosine waveforms. For single pulse inputs this method leads to some very difficult mathematical problems.

Amplitude-time analysis methods have become increasingly popular in recent years. This approach to system behavior is inherently more realistic in many cases, as it describes the input and output amplitude changes in real time. Laplace (or Heaviside) transform is the mathematical method, and inputs which change suddenly or have strange non-recurring waveforms can be easily described analytically.

Very recently, statistical methods have been applied to the analysis of servomechanism behavior. These are basically amplitude-time methods, but are at present of rather limited application.

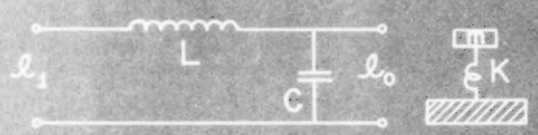


Figure 1

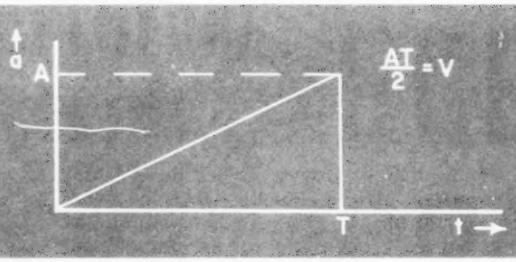


Figure 2

The two methods of systems testing which arise from these analysis methods are "swept sine wave" and "pulse." The swept sine wave is the familiar approach of plotting output amplitude and phase against input for a sine wave with variable frequency. With pulse testing, output is measured for an input which consists usually of a train of pulses of suitable waveform spaced far enough apart in time so that the output due to any one pulse has died away before another pulse is applied. This is now the usual method for testing communication systems, and is frequently used in the study of servomechanisms.

For a "linear" system (i.e., one in which no amplitude distortion occurs) the results of either test method are deducible from those of the other, but real physical systems are often not even approximately linear. Then judgment and trial-and-error are needed to show which approach will give the most useful results.

Much of the effort which has been put into the mechanical testing of tubes has been by the amplitude-frequency system. Most special purpose tubes have specifications for behavior under sinusoidal vibration, often with the frequency swept over a wide range. A plot is obtained of output voltage against vibration frequency at a fixed peak acceleration, which can then be interpreted by a customer in terms of the known vibration environment of his equipment. Swept-frequency tests generally take considerable time and need skilled interpretation. These are often objectionable requirements. Another objection often made to this type of test is that in real life, with a system which may be non-linear, all the important vibration frequencies are usually present simultaneously, so that the summation of results from separate application of each frequency may not cause the same behavior as tubes will have in use. Indeed, the mechanical behavior of tubes is not linear.

Two methods of applying a large number of frequencies simultaneously have been used: random noise excitation and "shock" testing. Tubes are vibrated with a signal derived from a "white" noise generator, which excites all frequencies equally. The drawback is the same as with "hi-fi," namely that prohibitively large power reserves are needed in the generator so that occasional random peaks are not distorted by overloading of the vibration equipment.

The other method, shock testing, is becoming increasingly popular. This is an amplitude-time approach, and means the subjection of the component under test to a sudden change in speed. The shock in question is then the acceleration-time waveform of this speed change. It will be seen that in general three quantities must be specified to describe a shock pulse completely, one of which must always be the waveform. The others can be the peak height and duration, the area and duration, or the area and peak height. The impulse is the only exception to the rule that three quantities must be specified to define a pulse. Only the area is specified for an impulse, as the duration is defined as being vanishingly small compared with the period of any resonant frequency of the object under test.

Now, how can it be said that changing the speed of a component suddenly is equivalent to vibrating it at a number of frequencies simultaneously? To show that the analysis that follows is not just a flight of fancy, imagine a golf ball full of small bells, each of a different pitch. Now if the ball is given some speed by teeing off, one can imagine the bells all sounding as if they were being rung.

More exactly, consider a large rigid mass to which a small object of mass m is attached by a spring of stiffness K. Then, if the accelerations of the large and small mass are considered, the electrical analogue of the system is as shown in Figure 1, in which ℓ_1 is equivalent to the acceleration of the large mass M; ℓ_o is equivalent to the acceleration of the small mass m; L is equivalent to the spring compliance, 1/K; and C is equivalent to the small mass m. The transfer function of this electrical system is:

$$\ell_o(s) = \ell_1(s) \left\{ \frac{\frac{1}{sC}}{sL + \frac{1}{sC}} \right\}$$

and calling $LC = 1/\omega_o^2$,

$$\ell_o(s) = \ell_1(s) \frac{\omega_o^2}{s^2 + \omega_o^2}$$

Now take the acceleration waveform as being due to decelerating the large mass from a steady speed V to rest with a constantly increasing force, giving the acceleration-time waveform shown in Figure 2. The equation of this line is $t = (T/A)a$. The Laplace transform can be found in the following fashion: the rising waveform has the transform $(A/T)\ (1/s^2)$, which is brought to zero at time T by a step $-Ae^{-sT}/s$, and maintained at zero by a falling waveform $(-A/T)\ (e^{-sT}/s^2)$. Thus,

$$\ell_1(s) = \frac{A}{T}\frac{1}{s^2} - \frac{A}{T}\frac{e^{-sT}}{s^2} - \frac{Ae^{-s}}{s}$$

The acceleration of the small mass during the shock is given by:

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$$= \frac{\omega_o^2 A}{T}\frac{1}{s^2(s^2+\omega_o^2)}$$

$$\ell_o(t) = \frac{\omega_o^2 A}{T}\left(\frac{1}{\omega_o^3}\left[\omega_o t - \text{Sin}\,\omega_o t\right]\right)$$

$$= \frac{A}{T\omega_o}\left(\omega_o t - \text{Sin}\,\omega_o t\right)$$

$$= \frac{A}{T}t - \frac{A}{T}\frac{\text{Sin}\,\omega_o t}{\omega_o}$$

This is the original waveform with a sine wave superimposed on it of amplitude proportional to the acceleration-time slope and inversely proportional to the resonant frequency of the small mass-spring combination.

For anyone who has seen the results of this analysis quoted without the detailed steps it should be explained that as damage (or microphonic output) can normally only be caused by deflection of the spring, the At/T term is not part of the shock spectrum. A common confusion that arises from this is between transmissibility and potential damage. In any discussion of this type the original waveform should be subtracted from the spectrum obtained, unless the small object itself is acceleration sensitive.

For t greater than T, the new accelerations generated by the end of the pulse are given by

$$\ell_o(s) = \frac{\omega_o^2}{s^2+\omega_o^2}\left(-\frac{A}{T}\frac{e^{-sT}}{s^2} - \frac{Ae^{-s}}{s}\right)$$

The first term is the same as the waveform during the pulse but of opposite sign. The second term is

$$\ell_o(s) = \frac{\omega_o^2}{s^2+\omega_o^2}\left(-\frac{Ae^{-sT}}{s}\right) \quad ;$$

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$$\ell_o(t) = -\omega_o^2 A\left(\frac{1}{\omega_o^2}\left[1 - \text{Cos}\,\omega_o\,(t-T)\right]\right)$$

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The term $-A$ cancels the value $+A$ generated by At/T during the pulse, which reaches this value at $t = T$. Thus if the resonant frequency of the mass on the spring is high enough for $(A/T\omega_o)\ (\text{Sin}\,\omega_o t)$ to be small compared with $A\ \text{Cos}\,\omega_o\,(t-T)$, the acceleration of the small mass will simply be proportional to the peak height of the triangular shock. It will be seen that this is true whatever the resonant frequency may be, so that the large mass appears to have been vibrated uniformly at all frequencies above some minimum.

Other acceleration waveforms give similar results, with, however, widely different relations between resonant frequency and amplitude. Figures 3, 4 and 5 show the acceleration-frequency relationship for half-sine, triangular, and rectangular acceleration shock pulses. The frequency ratio R is the ratio between the natural frequency of the small mass-spring system and the characteristic frequency of the shock pulse, π/T. The acceleration ratio is the peak acceleration of the small mass divided by the peak shock acceleration. The triangular shape described is unique in

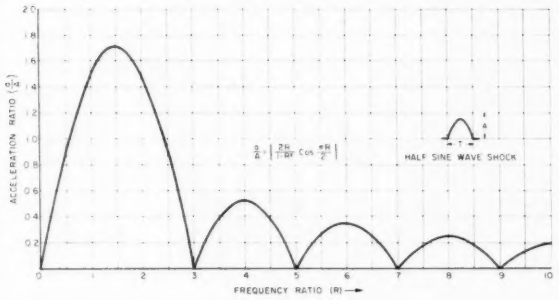


Figure 3

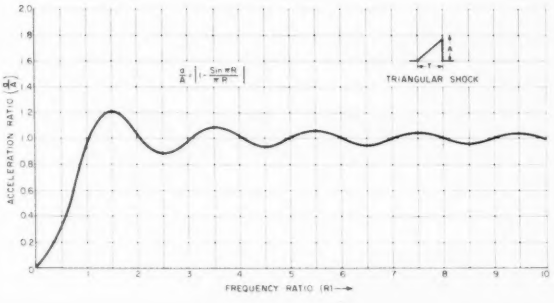
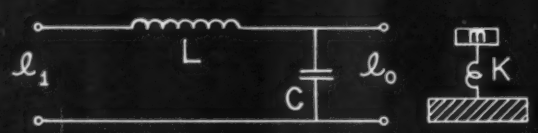


Figure 4



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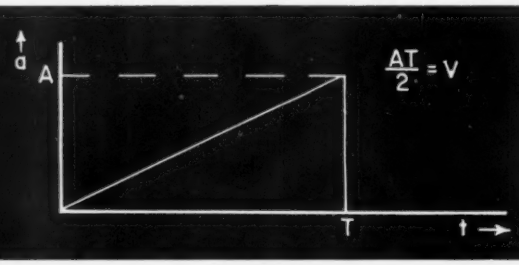

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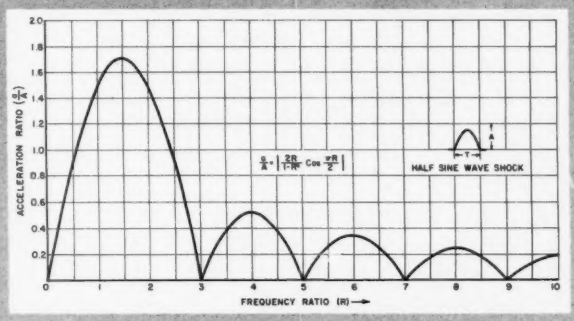


Figure 3

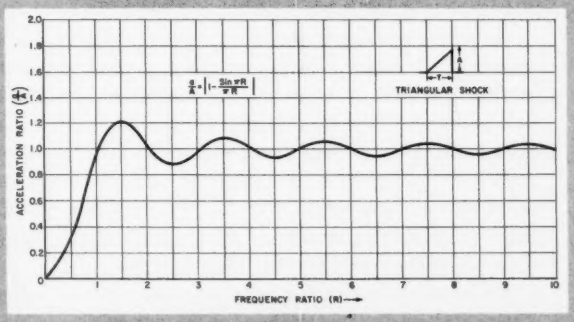


Figure 4

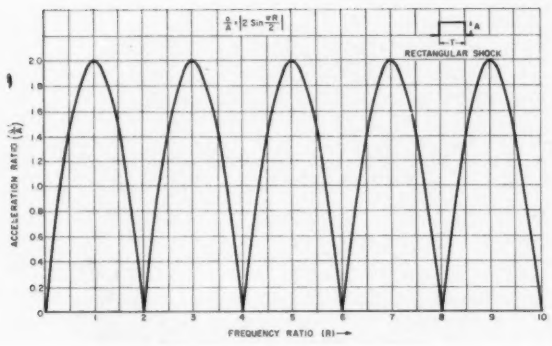


Figure 5

giving uniform excitation over a wide frequency band. It will be noted, however, that it is not equivalent to noise vibration since the phase of vibration of any mass-spring system is uniquely determined, as opposed to being random in the case of white noise.

The relationship between vibration testing and shock testing of tubes can now be seen. The common shock waveforms used are triangular, rectangular, half sine, and impulse. We need then a method of generating each of these waveforms.

The half-sine pulse is the easiest to generate for small speed changes (zero to about 10 mph), as the waveform generated by simple elastic collision is of half-sine form. If a weight is allowed to fall freely onto a rubber pad the acceleration imparted by the rubber pad will approach half-sine form. This is a common method of generating such a shock. For considerable velocities and displacements, for instance 100 mph, pneumatic and hydraulic methods have been used. Figure 6 shows two acceleration pulses generated by the same velocity change occurring in different times.

Impulsive accelerations are generated by inelastic collisions, for instance collision with a bed of sand over a large area, but rebound must be avoided if the velocity change is to be known accurately.

Rectangular and triangular waveforms are usually generated by using the special properties of lead. To a reasonable approximation the resistance of a large body of lead to the insertion of a spike is proportional only to the largest cross sectional area of the spike within the lead. Thus, a plain cylinder of steel forced into lead by a falling carriage will give approximately constant force on the carriage, and hence constant acceleration. Similarly, a tapered spike will generate a triangular acceleration pulse. A machine is on the market which achieves similar results by crushing shaped lead pellets between flat plates.

These are some of the most common methods of generating shock pulses. There is also a wide choice of methods of generating the velocity which is to be lost during the desired pulse. The most popular motive force is gravity in "free fall" or pendulum machines. Air guns, explosives, rockets, hydraulic motors, springs, and many others have been used, and of these the most successful is the air gun. Of course, the acceleration-time waveform of the velocity generation must be of low height and long duration or it may be as much a hazard to the component under test as the desired test waveform.

A word about "tap" testing of components, particularly tubes, might not be out of place here. Tap testing means the application of a shock pulse of unknown waveform, height and velocity change to an indeterminate point on a tube envelope. The results of such a test are somewhat difficult to relate either to other tests or real environments. Because of the extreme simplicity of the apparatus needed (a small hammer), much work has been done on this type of test. No good ever came of it.

One of the most difficult aspects of shock testing is measurement of the shock waveform. As one cannot know beforehand what particular band of frequencies excited by the pulse will be important, the pulse shape must generally be accurately known. This supposes a measuring system whose response extends from virtually dc to a frequency well above the highest which can be excited by the pulse to an appreciable amplitude.

Strain gauge transducers are used to obtain measurements to dc, but in the common forms have limited high frequency response. Piezoelectric devices have good high frequency response (at least one on the market claims to have a first resonance at 150 kc/s) but need very special instrumentation to be useful at low frequency.

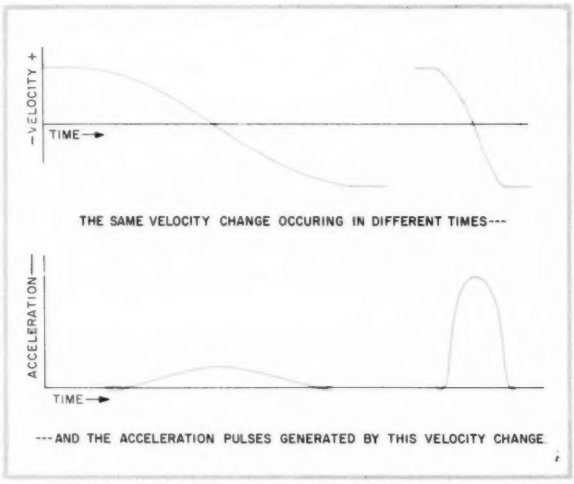
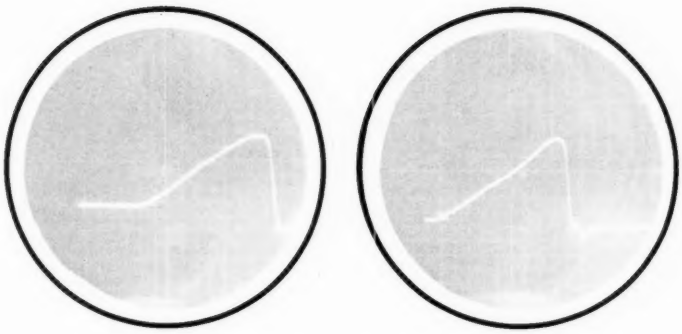
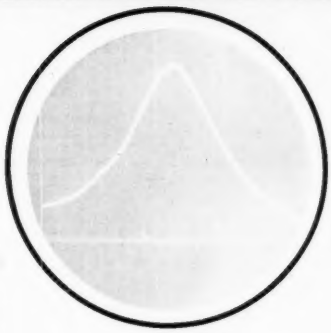


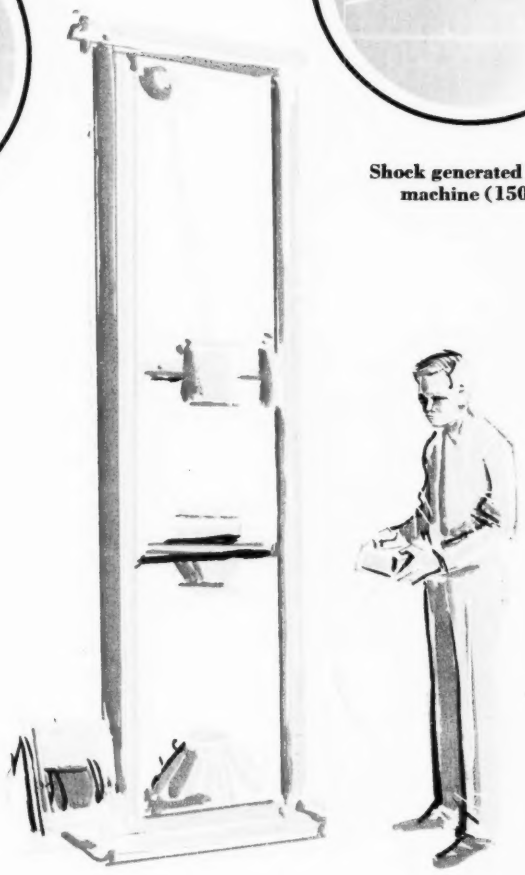
Figure 6



Triangular shock waveforms (100g, 4ms)



Shock generated by pneumatic machine (150g, 11ms)



The accelerometer response required can easily be predicted from the expected shock waveform, and the instrumentation designed accordingly. For instance, for a 30 millisecond duration pulse of half-sine waveform, response flat from 0.1 c/s to 1 kc/s will give a reasonably accurate picture of actual pulse shape, but for testing tubes the high frequency response should be extended to about 50 kc/s.

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At one extreme is a requirement for a 150 "g", 30 milliseconds duration half sine wave shock (a "g" unit of acceleration is 32.2 ft/sec/sec). The velocity change is about 60 mph, and the distance travelled during the shock is about 17 inches. In other words, this is similar to the shock generated by driving a car at 60 mph into a concrete wall. Contrary to what you might expect, small electron tubes stand up well to this test, principally because a half-sine wave does not appreciably excite the high frequencies to which tubes are sensitive.

Toward the opposite extreme is a 500 g, 1 millisecond shock. The velocity change involved is about 10 mph, much less than that previously mentioned. This test is, however, very bad for tubes, as high frequencies are excited and the peak acceleration is extremely high. The force applied by the shock per unit weight of the component is of course numerically equal to the peak acceleration in g units.

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It will be seen that the theory of shock testing and the analysis of results may be difficult and complicated, and are often misunderstood. In the future, however, the use of shock testing will be much expanded because of the inherent simplicity of the actual test and the tremendous saving in time over vibration tests. Vibration testing will continue to be used extensively, particularly for diagnostic purposes. Shock testing will probably prove more suitable for production testing of large numbers of small components and in this field should eventually replace vibration testing.

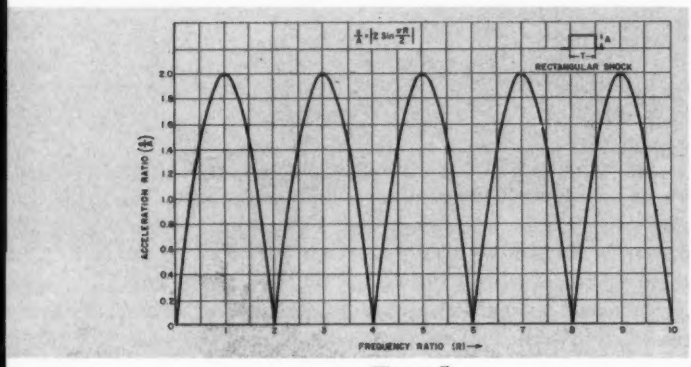


Figure 5

giving uniform excitation over a wide frequency band. It will be noted, however, that it is not equivalent to noise vibration since the phase of vibration of any mass-spring system is uniquely determined, as opposed to being random in the case of white noise.

The relationship between vibration testing and shock testing of tubes can now be seen. The common shock waveforms used are triangular, rectangular, half sine, and impulse. We need then a method of generating each of these waveforms.

The half-sine pulse is the easiest to generate for small speed changes (zero to about 10 mph), as the waveform generated by simple elastic collision is of half-sine form. If a weight is allowed to fall freely onto a rubber pad the acceleration imparted by the rubber pad will approach half-sine form. This is a common method of generating such a shock. For considerable velocities and displacements, for instance 100 mph, pneumatic and hydraulic methods have been used. Figure 6 shows two acceleration pulses generated by the same velocity change occurring in different times.

Impulsive accelerations are generated by inelastic collisions, for instance collision with a bed of sand over a large area, but rebound must be avoided if the velocity change is to be known accurately.

Rectangular and triangular waveforms are usually generated by using the special properties of lead. To a reasonable approximation the resistance of a large body of lead to the insertion of a spike is proportional only to the largest cross sectional area of the spike within the lead. Thus, a plain cylinder of steel forced into lead by a falling carriage will give approximately constant force on the carriage, and hence constant acceleration. Similarly, a tapered spike will generate a triangular acceleration pulse. A machine is on the market which achieves similar results by crushing shaped lead pellets between flat plates.

These are some of the most common methods of generating shock pulses. There is also a wide choice of methods of generating the velocity which is to be lost during the desired pulse. The most popular motive force is gravity in "free fall" or pendulum machines. Air guns, explosives, rockets, hydraulic motors, springs, and many others have been used, and of these the most successful is the air gun. Of course, the acceleration-time waveform of the velocity generation must be of low height and long duration or it may be as much a hazard to the component under test as the desired test waveform.

A word about "tap" testing of components, particularly tubes, might not be out of place here. Tap testing means the application of a shock pulse of unknown waveform, height and velocity change to an indeterminate point on a tube envelope. The results of such a test are somewhat difficult to relate either to other tests or real environments. Because of the extreme simplicity of the apparatus needed (a small hammer), much work has been done on this type of test. No good ever came of it.

One of the most difficult aspects of shock testing is measurement of the shock waveform. As one cannot know beforehand what particular band of frequencies excited by the pulse will be important, the pulse shape must generally be accurately known. This supposes a measuring system whose response extends from virtually dc to a frequency well above the highest which can be excited by the pulse to an appreciable amplitude.

Strain gauge transducers are used to obtain measurements to dc, but in the common forms have limited high frequency response. Piezoelectric devices have good high frequency response (at least one on the market claims to have a first resonance at 150 kc/s) but need very special instrumentation to be useful at low frequency.

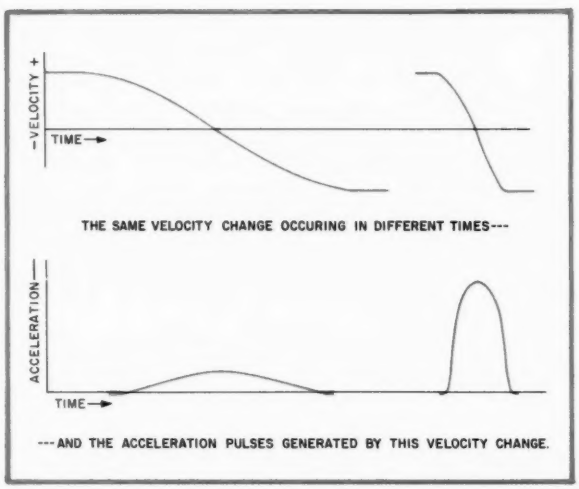
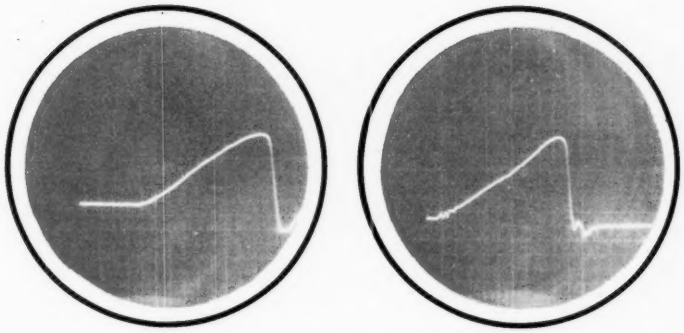
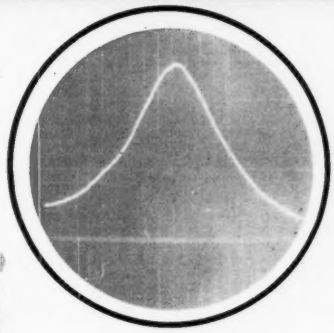


Figure 6



Triangular shock waveforms (100g, 4ms)



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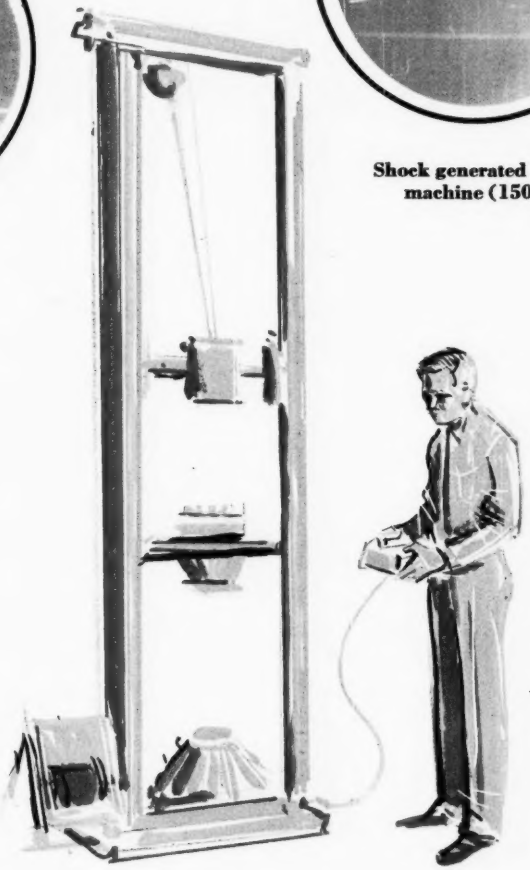

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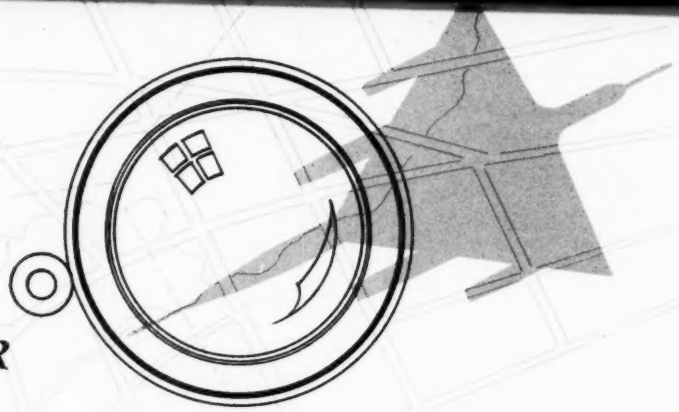

CHECKING THE ACCURACY OF A DOPPLER NAVIGATOR WITH PHOTOGRAMMETRIC MEASUREMENTS

G. Cooper
Maynard Laboratory

RAYTHEON has had a highly precise Navigational Doppler Radar, the AN/APN-113, under development for more than five years. This radar is being developed under subcontract to the Sperry Gyroscope Company for use in the B-58 Hustler. (Convair holds the prime contract from the United States Air Force for this aircraft and its subsystems.) The AN/APN-113 makes use of the Doppler effect to determine the ground velocity of an aircraft. Microwave energy is continuously transmitted toward the ground from three antennas arranged in the aircraft so that no two point in the same direction. Three receiving antennas, each pointed in the same direction as its associated transmitting antenna, receive the energy scattered back to the aircraft from the ground. As a result of the Doppler effect the received energy is shifted in frequency from the transmitted energy by an amount proportional to the projection of the ground velocity vector along the antenna direction. The three components of the ground velocity vector may be computed from the three Doppler shifts in relatively straightforward fashion. Considerable simplification of the computation can be achieved by a suitable choice of the antenna orientations.

A requirement for proving the accuracy of the AN/APN-113 in flight was established early in the development program. Since the Doppler Radar was required to be appreciably more accurate than existing velocity-measuring devices, this posed a rather difficult problem. Its solution: indirect determination of average ground velocity by measurement of ground distance traveled in a known time interval. Because the AN/APN-113 employs an antenna system fixed to the air frame, the components of the ground velocity vector are measured in an aircraft coordinate system. Aircraft attitude must, therefore, be measured in order to relate the aircraft coordinate system to the ground coordinate system. An unusual application of photogrammetric technique was selected to measure both ground distance traveled and aircraft attitude, because its accuracy was better than any other available means. This article discusses this technique.

Basic Principles of Photogrammetry

Photogrammetry deals with the measurement of ground distances through the use of photographs of the ground taken from an aircraft. Usually, photogrammetry is employed to obtain very detailed maps with a minimum of actual ground survey with transit and chain. Ground surveys of at least two points in each area covered by the aerial photographs are made. Distances to, and hence the position of, any other point can be obtained by scaling from the photograph. Corrections must be made for the tilt of the camera at the time the photograph is taken, but great precision in tilt measurement is not usually required. A rather convenient way to determine tilt makes use of a stereoscopic projection of two aerial photographs covering overlapping areas. By adjusting the projection angles for the photographs so that the three-dimensional image shows vertical objects appearing vertical, tilt is corrected.

If a more precise correction of tilt is required, an analytical method can be employed. The basis of this

method can be explained by the "one-dimensional" case illustrated in Figure 1.

With the camera level as shown in Figure 1(a),

$$\frac{ab}{bc} = \frac{AB}{BC} = \frac{A'B'}{B'C'}$$

because the triangles involved are similar. Thus, if the ratio of the distances measured on the photograph is the same as the ratio of the distances measured on the ground, there is zero tilt in the photograph. It is seen from the figure that this result is independent of altitude. However, if the focal length of the camera, f, is known, the altitude of the camera is given as either:

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In this special case, it is readily apparent that tilt and altitude can be determined by a comparison of measurements made on the photograph with measurements made on the ground. Defining camera position as the center of the photograph, the ground equivalent of camera position can easily be found.

Turning to the non-zero tilt case illustrated in Figure 1(b), it can be seen from the similar triangles that:

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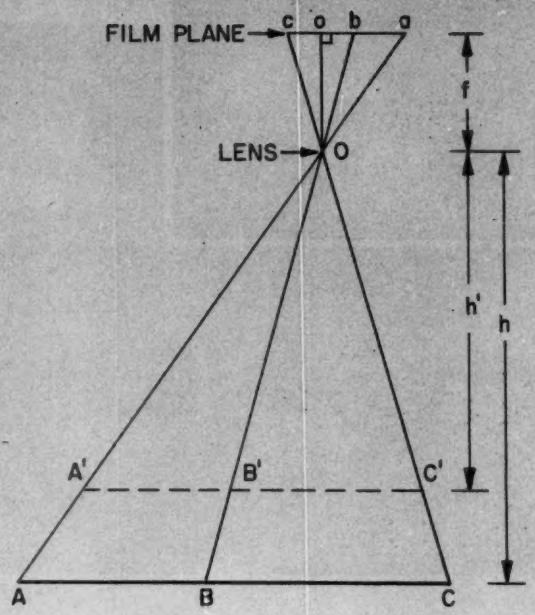
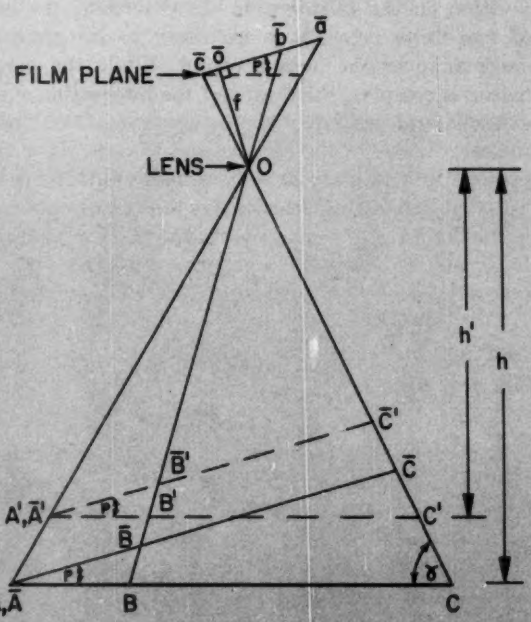
Another approach to the determination of tilt by analytical means has been developed by Professor Edward Young and his co-workers at the University

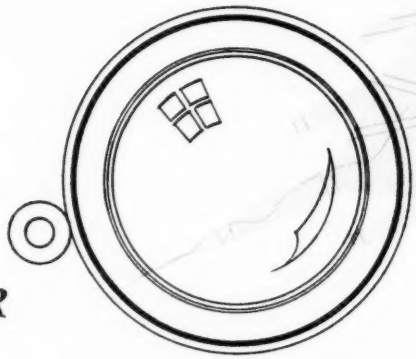


(a) Camera Level



(b) Camera Tilted

Figure 1



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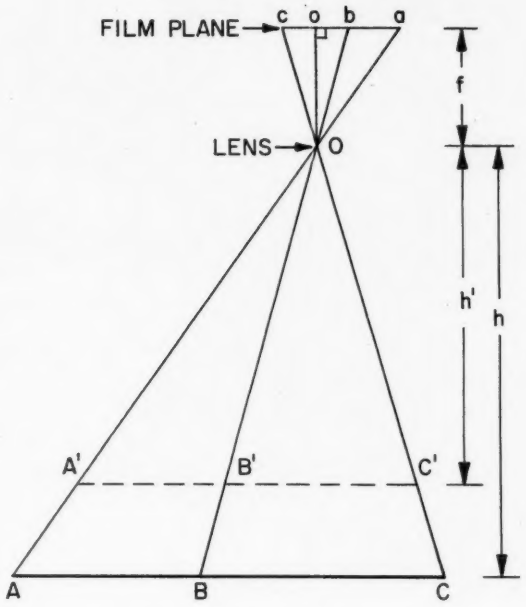

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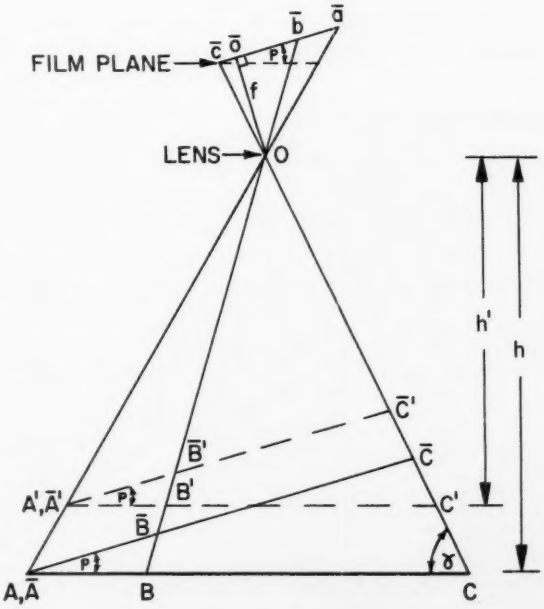

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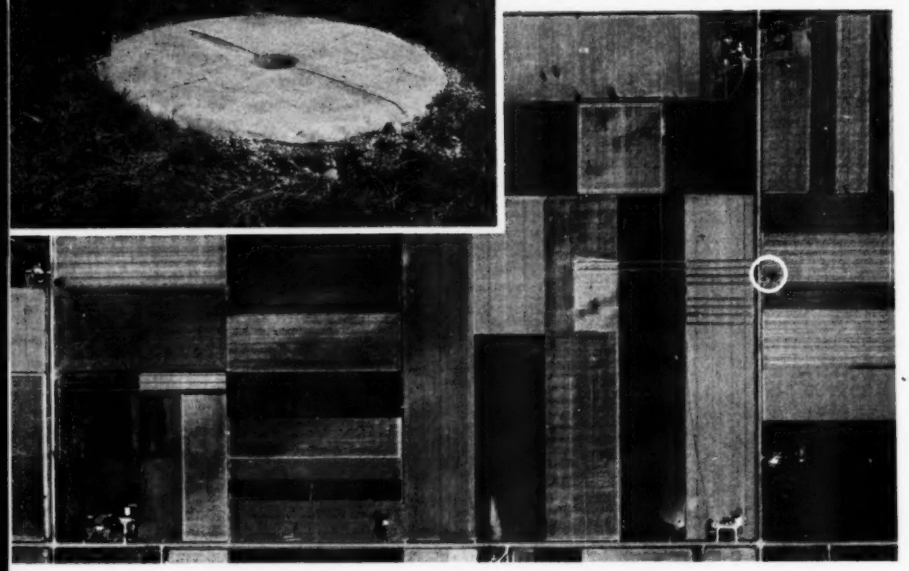
Figure 1

Figure 3



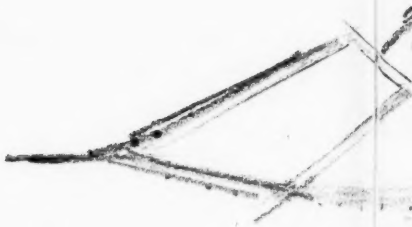


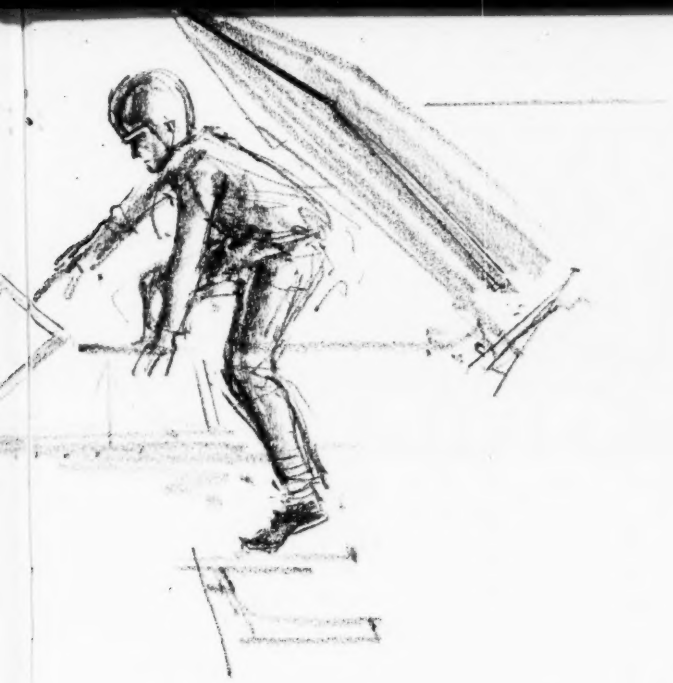
Figure 2

of Michigan. This approach is based on the comparison of areas on the photograph with the corresponding areas on the ground. The ratio of a differential area on the ground to its projection on a tilted photograph is given by the Jacobian of the transformation from a level coordinate system to the tilted coordinate system. The Jacobian is a function of the tilt and the position on the photograph. To determine the ratio of two finite areas, it is necessary to integrate the Jacobian over the area involved. While the mathematics is complex, the results of the integration over a quadrilateral are fairly simple algebraic functions of the coordinates of the corners and the tilt. It is then possible to obtain a relatively simple solution for tilt. This solution is also less sensitive to errors in measurement than the pyramid method. While it requires four points per solution compared to three points for the pyramid method, this is not at all a disadvantage.

Photogrammetric Determination of Aircraft Position and Attitude

If the aerial camera is boresighted to the aircraft axis, aircraft attitude is given by the components of camera tilt. Furthermore, if the position of any desired point on the aircraft is measured with respect to the center of the film plane, its position relative to the ground can also be determined. These steps are not included in the usual applications of photogrammetry, but their addition is all that is required for a photogrammetric determination of aircraft position and attitude. The advantage of this method is the extremely high accuracy which can be achieved. Aircraft attitude is currently being measured to about 10 seconds of arc and aircraft position to about ½ foot (at an altitude of 9,000 feet).

Flights for these purposes are carried out over an area in which there are a number of well-surveyed markers. There are three major photogrammetric ranges in the United States: Eglin AFB, Florida; McClure, Ohio; and Phoenix, Arizona. These ranges are situated in flat terrain and contain artificial markers of varying descriptions. Figure 2 is an actual photograph of a portion of the range at McClure, Ohio, taken in the course of one of Raytheon's accuracy flight tests. The markers are barely discernible to the naked eye. Marker number 65 which has been given the code name Mate is circled on this photograph. Figure 3 is a photograph of the marker itself. It is a six-foot disc of concrete poured on the ground. A U.S. Coast and Geodetic Survey Monument is located at its center and its position has been determined in a first-order survey. This marker is typical of those to be found at the McClure Range. There are about 90 of these markers over an area of about five square miles, giving an average spacing of about ½ mile between markers. This range has been designed for flights at altitudes from about 8,000 to 10,000 feet. The range at Eglin AFB has been designed for an altitude of about 20,000 feet, is about 30 miles long, and employs concrete markers having a checkerboard pattern painted on top with squares about six feet on a side. The range at Phoenix is designed for an altitude of about 30,000 feet, is also about 30 miles long, and uses some checkerboard markers and some natural markers (road intersections). It is not as accurately surveyed as the other two ranges.



In an actual flight test, the aircraft flies back and forth over the range, with photographs being taken at intervals determined by an accurate timing source on board. For the Raytheon tests this time interval has been two seconds. After development, the film is read by means of an optical comparator. One such comparator, made by Gaertner Scientific Instruments, is shown in Figure 4. All the film reading and photogrammetric data processing for the Raytheon tests have been performed by personnel at the University of Michigan. The first step in the reading process is the identification of the markers on the photograph. As a rule twelve markers are identified (by grease pencil circles) on each photograph to permit three independent tilt and position determinations by the area distortion method. A photograph is then inserted into the comparator and the film axes (defined by fiducial marks on each photograph) are aligned with the comparator axes under tremendous magnification. A micrometer screw motion is used to set cross-hairs over each marker in turn; magnification is such that the actual center of the disc can be determined. The photographic coordinates of each marker with respect to the film axes are read off in the same way that one reads a micrometer. Positions can be read to one micron and are repeatable to better than five microns. One micron on the photograph corresponds to 0.7 feet on the ground. In the reading, one operator uses the comparator and reads off the coordinates to another person who records them. The operators interchange functions to help reduce fatigue. It takes about 45 minutes for a skilled, fresh operator to read one photograph. More than half of this time is used in aligning the film axes and comparator axes.

After the photographs are read the data is punched on IBM cards, and the solution for tilt and position is carried out on a digital computer. In this solution corrections are made for linear film shrinkage (the spacing between the fiducial marks being the basis for correction), lens distortion (accurate measurement of focal length over the entire lens aperture being the basis for this correction), and atmospheric refraction. Large differences among the three independent solutions indicate reading blunders, which are then checked out. Photographs are reread to remove such blunders. Only 20% of the photographs usually have to be reread.

Conclusion

To solve the difficult problem of checking the accuracy of a highly precise Doppler navigational radar, the AN/APN-113, Raytheon has made use of an unusual application of photogrammetric technique to determine aircraft position and attitude at known intervals of time. While this technique is time consuming and costly, it does provide the extremely accurate independent measurement of aircraft velocity required to check the accuracy of the AN/APN-113.

Figure 4

key to better engineering practices

C. W. Watt
Office of the Vice President
Engineering and Research

THE word "standards" is so loosely used today that it is important at the outset to distinguish the two major applications of the term. The word, in its oldest engineering sense, is defined in the American Collegiate Dictionary as "the authorized exemplar of a unit of weight or measure." The National Bureau of Standards establishes weights and measures for the USA, and any scientific or engineering organization dealing with physical quantities must maintain local measurement standards based on these precisely established national standards. Such local standards are absolute necessities in any technical industry today, and Raytheon has an extensive system of primary and secondary measurement standards laboratories, which are constantly being improved. The second kind of standards, related more to a setting of levels of excellence, may be termed "standards of engineering practices and procedures," and the present discussion will confine itself to establishing the latter meaning and to indicating some of the present efforts and future plans at Raytheon for obtaining benefits from such standards.

An engineering standard, as it is defined here, is an accepted solution to a recurring engineering problem. The key words are "accepted," "recurring," and "engineering." An examination of the implications of these words leads to further clarification of the basic concept of standards engineering.

The word "accepted" implies prior agreement; hence, much of the work of preparing a standard is in bringing people together and securing their agreement on a satisfactory solution to a problem. This is as much diplomacy as engineering, but it is an absolutely essential part of the job, no matter what industry or trade is involved.

The second key word is "recurring," a word which serves to introduce the natural economic limitations inherent upon efforts in this field. Obviously there is little benefit in spending more money to secure agreement than this agreement would be worth in terms of lowered cost of engineering or manufacture, or in the production of a better item.

The third key word mentioned above is "engineering." This sets both the technical and administrative limits of the work, for standards are applied most effectively during the design phase of a job. Manufacturing and purchasing and quality control all benefit and must all be consulted in the development of an engineering standard, but the use of the standard must be initiated during the engineering phase of a project. Procedural standards — drafting procedures, release procedures, etc., — likewise directly affect the manufacture of a product by helping or hindering the transmission of information between the engineering department and the manufacturing service, but they too are first applied by engineering.

In the brief analysis just attempted of the key words in our basic definition, several more words showed up that give us a broader view of what standards engineering is. Phrases such as "lowered cost of production," "highest reliability," "transmission of information" are important. They indicate that an ideal standard represents the combined efforts of many experts in different fields: components and materials, reliability and quality control, cost reduction and value engineering, purchasing, and manufacturing.

Raytheon is, of course, analagous to a Federal Union, with the Federal Government, or Corporation, having certain legitimate interests, but with the States, or Divisions, having large areas of local autonomy. This is true of all activities in the Company. With regard to standards engineering in particular, efficiency demands that the areas of common interest between divisions be organized and administered on a common basis; efficiency, flexibility, and diversity of products demand that problems of local interest be

solved and administered on a local basis, with the interest of the corporation in these local problems properly limited to insuring compatibility between divisions, to insuring good communications between divisions, to providing a center of information on any of the subjects within its scope, and to providing, on request, certain consulting or assisting services.

This is, in fact the way standards engineering at Raytheon is organized. Divisional effort has been extensive over the years, and many groups of men dedicated to higher engineering efficiency have done an excellent job. Corporate activity has been growing as the Company has grown larger and more diverse. Today the corporate standards engineering work is part of a unified corporate effort which performs a policy-making and coordination function in the following fields:

1. Engineering standards and their application in the design, development, and release of new equipment.
2. Cost reduction techniques and their application in the design, development, and release of new equipment.
3. Component application engineering as it pertains to the design of equipment.
4. Reliability engineering.
5. Standards and definitions of measurement.
6. Interdivisional communication on any one of the above subjects.

The respective effort to be put forth in the future by the divisions and by the corporate group must be defined dynamically with respect to the conditions existing today, and be flexible enough to change with changing conditions.

The corporate group was established only recently. Before it was formed representative people in the various divisions were first polled in a very informal way. In conversations with engineers, designers, purchasing and manufacturing people, and standards and components engineers, the status of work in the broad area here defined as standards engineering was outlined. People from all the operating divisions were contacted and their ideas and opinions were digested. To establish a definitive channed for continuing such a dialogue a Standards Advisory Committee was then set up, with members from each division.

The central agency that has resulted from these interchanges includes standards as one of its major interests, but as indicated above must be competent in related areas also. This agency, known as the Corporate Office of Engineering Practices, serves first of all as the coordinating point and information center for all Raytheon activities in the fields discussed above. The functions of this office include the following:

1. Acting as the Raytheon spokesman for all corporate dealings with the government, trade associations, professional societies, etc., on any of subjects mentioned above. That is, when Raytheon must speak as a corporation, divisional opinion will be coordinated by and expressed publicly through this office. This function is illustrated by Raytheon's response to a request from the Electronic Industries Association for comment on a proposed Military Drafting Standard. Numerous individuals in six divisions offered their comments and the Office of Engineering Practices sent one letter to the EIA combining these comments in a single answer from Raytheon.

2. Serving as a clearing house for information on all divisional activities in these fields. Complete files on who is doing what in the Company are maintained, and the Office provides quick service to put a man in Andover in touch with a man in Santa Barbara who has wanted information — or even another man in Andover. The rapid growth of the Company and the large number of new people unacquainted with the organization of any but their own groups makes this service a valuable one in reducing lost and unproductive time.

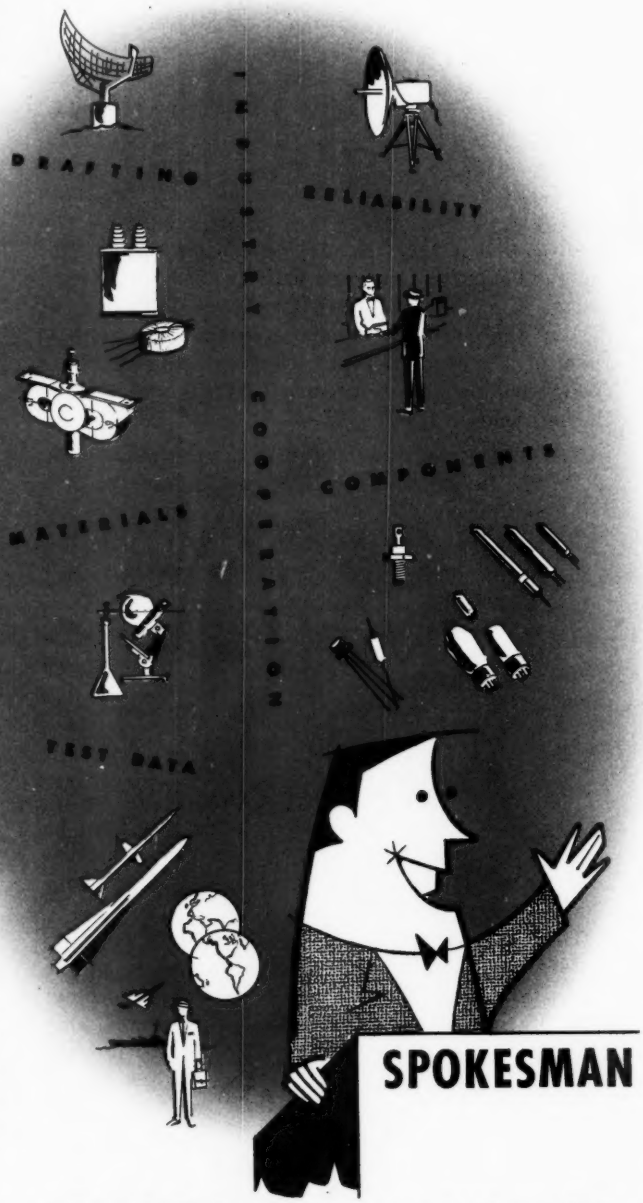
3. Maintaining records of the existence and location of publications of trade societies, such as ASTM standards, EIA standards, etc., and maintaining full records on Company membership in trade societies, with the names of all Raytheon personnel in all divisions who serve on the various committees of such societies.

4. Maintaining files on certain Military Specifications and Standards, and being prepared to issue them to individuals on request. This cannot be a complete specification issuing service, simply because there are so many of the Military Specifications — boxcars of paper and a large clerical staff would be required to do a halfway job, a job that is much better handled generally by the project groups using the specs. Files of common specs are maintained, as well as complete indices, and a complete listing of all major repositories of the Military Specifications in the Company is kept. Thus this Office can be an important place to check before trying elsewhere for anyone needing a particular specification. The chances are very good that he can be directed to the holder of the spec in the Company.

5. Maintaining complete files of all pertinent Raytheon Divisional Standards and preferred practices.

Because of the dynamic nature of standards engineering it is essential that the work in this field be done by experienced engineers who have a close and sympathetic understanding of the problems of the design engineers. Most of these engineers are of course located in the divisional standards engineering groups. The corporate agency, however, takes a great deal of interest in the people in these various divisional groups; as time goes by it is expected that the corporate Engineering Practices Office will sponsor programs for the growth of the standards and components engineers throughout the Company. There are also some areas of activity that are common to all the divisions, or at least to several of them, and it is for this reason, as well as to provide technical competence at the corporate level for the purpose of monitoring the work of and improving the status of the divisional standards and component engineers, that a small unit of experienced engineers is maintained by the Engineering Practices Office of the Corporation. These engineers are divided into three groups, the standards and specifications engineers, the components applications engineers, and the reliability engineers. These groups report to the Director of Engineering Practices, who reports to the Vice President, Engineering and Research.

The first of these corporate groups concerns itself with practices and procedures that have multi-divisional application. This group must identify, first of all, the economic and technical need for uniform practices (for example, common military drafting practices and a common format for purchase specifications); guide the documentation of such practices, always with extensive divisional participation; obtain divisional concurrence; and monitor their usage. This involves a thorough understanding of divisional requirements, a knowledge of people, and a good technical background.



Acting as the Raytheon spokesman on engineering standards . . .

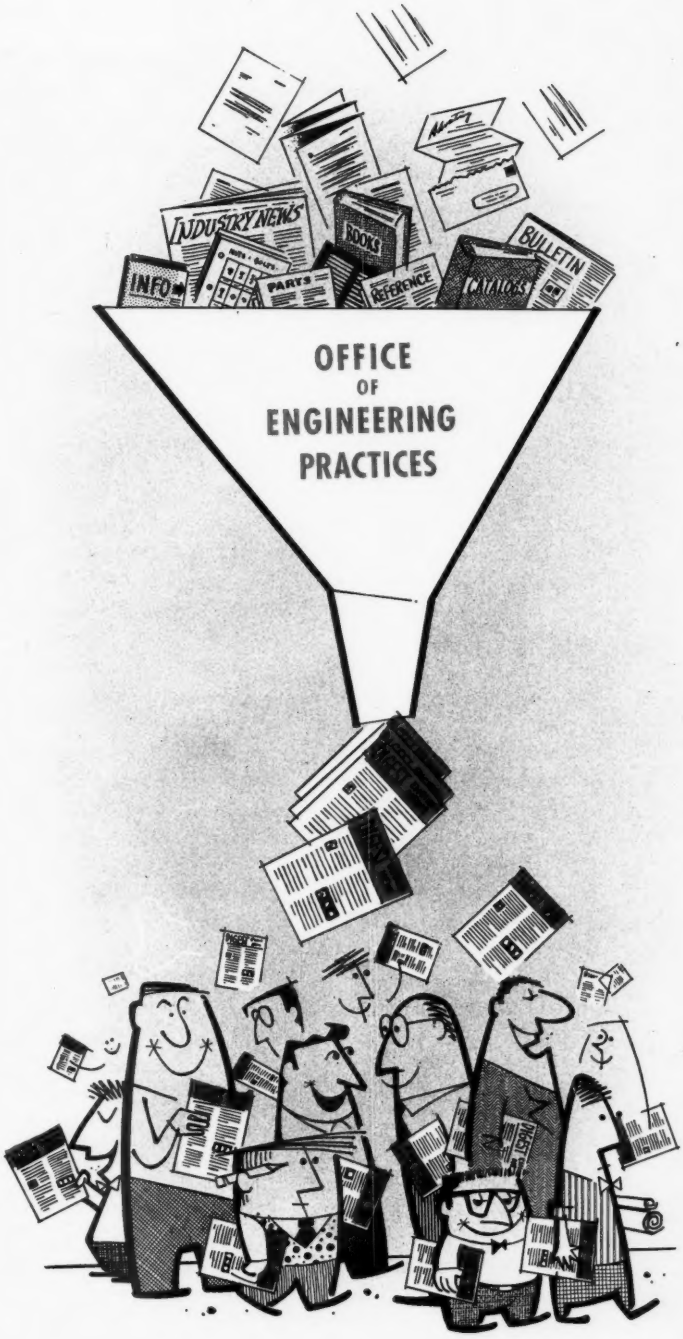
The second group concerns itself specifically with those components, materials and processes that are *not yet* "standard" at all, even in the divisions. The component and material arts are changing at such a rate that no one charged with responsibilities for a specific project can keep entirely up to date. Likewise the work of evaluating components for specific projects is so large that little manpower and time is left for looking ahead — and looking around — to see

what new things are becoming available that will improve the product of tomorrow. This group, small but competent, is charged with the function of looking around, and making at least preliminary evaluations and recommendations to the operating divisions on components of new varieties that may be useful to them. These engineers, too, will spend some of their time in the divisions as consultants, helping the components engineers on the job, as well as becoming more closely acquainted with current and future problems that involve components and materials. This group also has the responsibility of preparing and presenting seminars or training courses on components for the specific purpose of improving the knowledge and competence of component application engineers in the divisions.

The third group's main function is to develop a sound corporate policy for equipment reliability control, with the cooperation and assistance of the reliability groups in the divisions. Further, once this policy is put into effect, this group will have the job of monitoring its application, and will represent corporate management as necessary in general discussions or negotiations with the customer regarding reliability of equipment developed or manufactured by Raytheon.

Finally, the corporate Engineering Practices staff, as a whole, strives to improve communications on standards, components, materials, product design techniques, cost reduction techniques, and reliability throughout the Company. It is the intention to begin the periodic publication in the near future of a "Digest of Engineering Practice" which will contain, in brief form, pertinent information on what is happening in the Company on these and related subjects. What form this will take and how widely it will be useful remains to be seen. Inter-group and interdivisional communication is a problem of major proportions and it will be a difficult one to solve completely. Much can be done to improve the situation, however, and a frankly experimental approach is being taken toward reducing duplication of effort and lost time due to lack of information as to what is going on.

The effort outlined above covers a wide range of activities and implies a vast amount of work. The bulk of the work will continue to be done in the divisions as at present. The corporate staff hopes to increase the efficiency of this work by providing spot help, consulting and better communications, and by removing from the work load of the divisions those chores that are common to two or more, thus providing "accepted solutions to recurring engineering problems."



Publication of a "Digest of Engineering Practice" . . .

The Formation of Silicon

A. H. Smith
Research Division

THE space age is continually requiring new materials to meet specific needs. Some of the most pressing needs stem from the high temperatures encountered when a rocket passes through the atmosphere. This temperature problem is reflected in the electronic industry in the development of high temperature electrical components. Semiconductor devices such as diodes and transistors are specific components for which higher temperature of operation is continually required. Their range of operation, however, is dependent upon the properties of the semiconductor used in that specific device. Silicon and germanium lose their semiconduction properties about 300°C and 150°C respectively. Silicon carbide remains a semiconductor above 1000°C. Because of this high temperature range of silicon carbide, considerable interest has developed in making single crystals of semiconductor purity from this material.

Controlled crystal growth of a substance may be accomplished by cooling a melt, growing from solution, or growing from vapor. Silicon metal is formed into single crystal ingots by pulling the solid phase from the liquid phase at about 1430°C. This method of cooling from a melt is not possible with silicon carbide inasmuch as it decomposes before it melts at atmospheric pressure. There is the possibility of growing silicon carbide from solution. Carbon is slightly soluble in molten silicon at the temperature at which silicon carbide is formed (about 1600°C). Crystals of silicon carbide can be obtained from this solution; however, the crystal shapes obtained are usually irregular prismatic forms, not large enough to cut up into plates, and not regular enough to be used in devices without cutting. This modification of silicon carbide, designated beta-phase, forms at temperatures below 2000°C. At higher temperatures up to decomposition the crystal modifications designated alpha are formed. These are normally hexagonal or triangular platelets suitable for device application without cutting. The growth mechanism for this temperature range is sublimation and recrystallization.

These crystal modifications have been known for some time, particularly in the abrasive industry. However, forming silicon carbide of sufficient purity for use in semiconductor devices is a project requiring much more refined techniques than those used commercially. Growth from a vapor appears to be the most promising method of obtaining semiconductor grade silicon carbide.

Let us consider the probable phase diagram of silicon and carbon to see why vapor growing is preferred over growth from the melt. Figure 1 shows the temperature, composition, and phase relationships at atmospheric pressure. On this diagram the decomposition of silicon carbide is indicated at about 2700°C. At this temperature silicon vapor, silicon carbide, and graphite are coexistent. Above this temperature only silicon vapor and graphite exist. For true vapor growth of silicon carbide the temperature must be kept below this value. Growth from the melt at atmospheric pressure is thus prohibited because of decomposition.

Possibly silicon carbide could be melted without decomposition at higher pressure. The effect of pressure on decomposition should therefore be determined.

At the decomposition temperature, 2700°C, the extreme pressures are determined by the vapor pressure of silicon on one side (about one atmosphere) and carbon on the other (about 10^{-4} atmosphere). It is evident because of the difference in vapor pressures at this temperature that the vapor consists largely of silicon. Study of the temperature-phase diagram shows this also.

Note the similarity between the pressure-composition diagram and the temperature-composition diagram. High pressures favor the condensed states, as do lower temperatures. It is reasonable to expect that melting without dissociation might be attained at elevated pressure. Combining these two curves leads one to believe this, although estimates of pressure required are not available. However, no vessel can contain the highly corrosive silicon vapor, the ambient in which melting would have to take place. If it were possible to contain the silicon vapor, no doubt the molten state of silicon carbide could be achieved. Large, essentially single crystal ingots could then be grown from the melt.

Carbide Crystallites

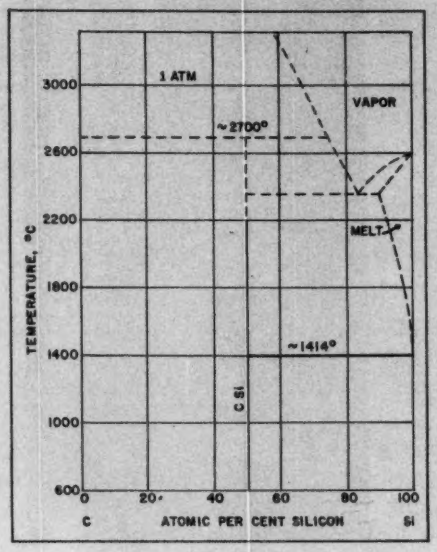


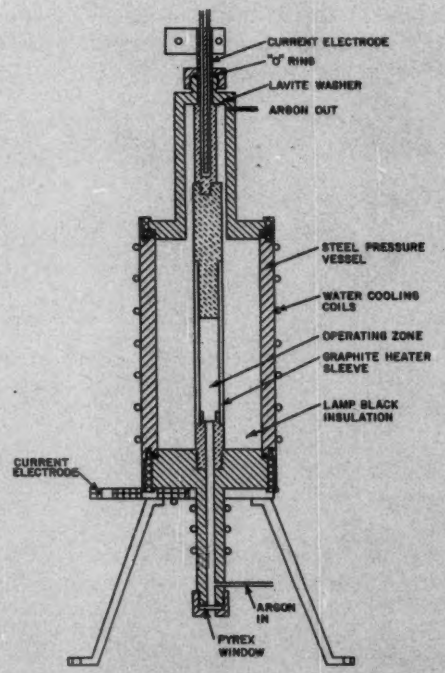
Figure 1

Since no way is known of arresting the corrosive action of the silicon vapors, the use of an all-carbon system is indicated. When all parts are assembled of high purity graphite the reaction with semiconductor grade silicon should result in high purity silicon carbide. The reaction of silicon vapors with the vessel can only add more of the desired silicon carbide crystals. Graphite is able to go to temperatures in excess of 3000°C before sublimation becomes excessive.

The approach of the experiment described here is basically different from the above methods. It involves the formation of crystals from the vapor, but not simply recrystallization of sublimed vapors. The chemical equilibrium equation $SiC \rightleftarrows Si + C$ is the foundation of the method. Ideally, one would like to combine pure silicon vapor with pure carbon vapor to form unattached silicon carbide crystals. When thinking of introducing silicon vapor into the working space, one is again confronted with the extremely corrosive nature of silicon. By holding the silicon in position in silicon carbide and releasing it as the above reaction changes the direction of equilibrium, the corrosive problem is quite well eliminated. The decomposition and recombination take place in the temperature range 2700° to 2800°C.

The silicon carbide used as starting material is the cubic beta-phase, formed by the reaction of silicon tetraiodide on carbon at 1600°C. A mixture of silicon and graphite powder may also be used as starting material. The silicon combines with carbon, forming silicon carbide during the temperature rise part of the program and is released at the decomposition temperature.

Figure 2 shows a longitudinal section of the pressure furnace. The heating element in this furnace is a graphite tube. Power for the furnace is controlled by a saturable core reactor on the input of a low voltage, high current transformer. 1000 amperes at 10 volts is an adequate supply for this furnace. The graphite screws into the base of the furnace. The upper electrode is isolated from the upper end of the furnace by an "O" ring which is also the pressure seal. Differential expansion of graphite to steel is accommodated by the friction fit piston in the sleeve.



GRAPHITE PRESSURE FURNACE FOR GROWING SiC CRYSTALS

Figure 2

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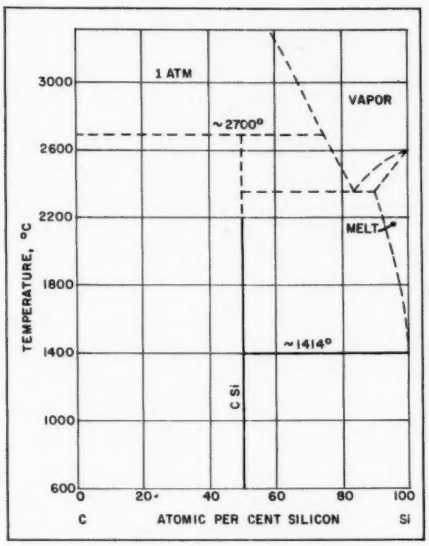

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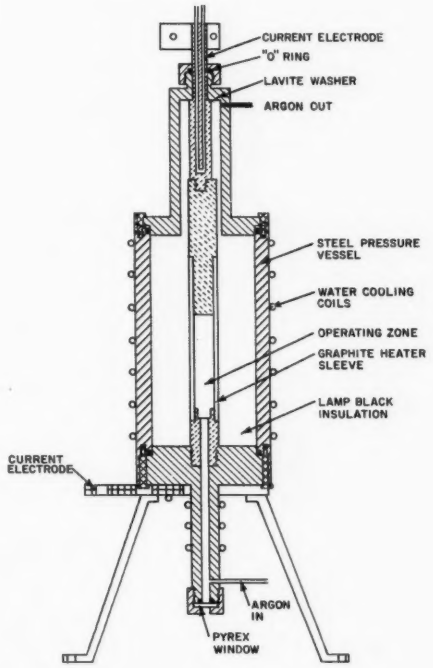


GRAPHITE PRESSURE FURNACE FOR GROWING SiC CRYSTALS

Figure 2

The space between heater sleeve and pressure vessel is filled with carbon black. Water cooling of the outside is necessary. About 4 kilowatts of power are dissipated in the apparatus at 2700°C and 100 psi of argon. The working space in this equipment is ¾ inch in diameter and 4 inches long.

The argon gas used as the ambient in this experiment is purified by passing over titanium chips at 800°C. The flow of the gas during an experiment is regulated by throttle valves in the range of 0.1 to 1.0 cubic feet per hour. Pressure in the furnace may be up to 1000 psi. The temperature is determined by viewing with an optical pyrometer through the porthole at the bottom.

The detail of Figure 3 shows the arrangement of crucible, reaction zone and collection zone. The crucible filled with silicon carbide is in a region where the temperature gradient is approximately 100 degrees per inch. The top is the hotter end. As the temperature of the furnace is raised to the reaction level, the silicon carbide in the top decomposes first. The silicon vapor diffuses downward since the upper direction is blocked by the graphite crucible. The temperature may be continuously raised until all the material in the graphite crucible is decomposed.

An example of this reduction action is shown in Figure 4, a cross section of the graphite crucible.

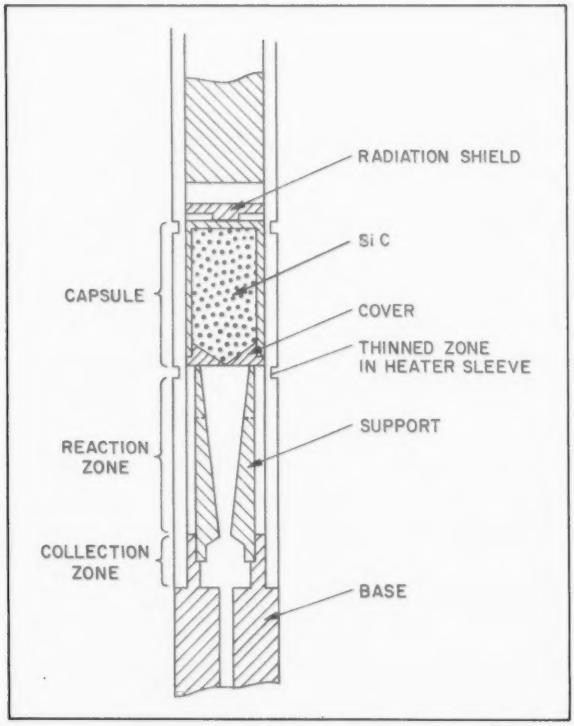


Figure 3

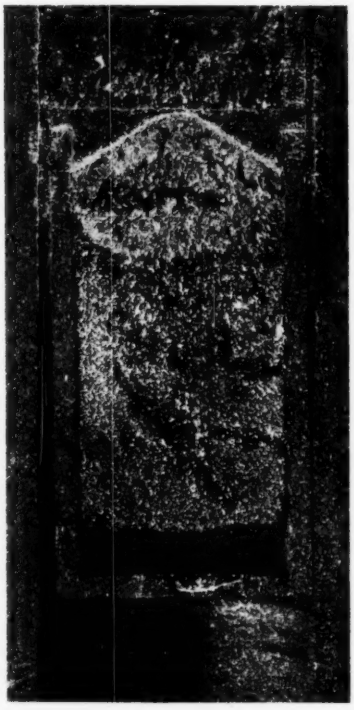


Figure 4

Most of the silicon carbide in the graphite cup has decomposed, leaving free graphite in the upper end. In this case the vapor pressure of silicon released in the capsule was enough to partially blow off the cup. This effect was observed even though the ambient pressure was 60 psi, because of the abrupt increase of the silicon vapor pressure at the dissociation temperature. X-ray diffraction studies of the material in the lower end of the crucible showed free graphite and silicon present as well as alpha-silicon carbide.

The experiment is one in which dynamic properties are used instead of static. The concentration of silicon vapor is high enough for crystal formation as long as the silicon carbide is decomposing. When it is gone, the experiment is over. The total time for a run is thus quite short. A typical temperature cycle is given in Figure 5. The temperature rise is about 25°C per minute from 1600° to 2500°C. Heating is slowed down as the reaction temperature is approached.

At the dissociation temperature, the released silicon vapor breaks through the thin graphite wall in the cover of the crucible and flake formation is spontaneous. As viewed in the pyrometer, the field of view becomes covered with flying crystals which show the distinctive hexagonal configuration as they fall in a tumbling manner. The apparent drop in temperature at the end of the run is due to masking of the hot reference surface by the silicon carbide crystals.

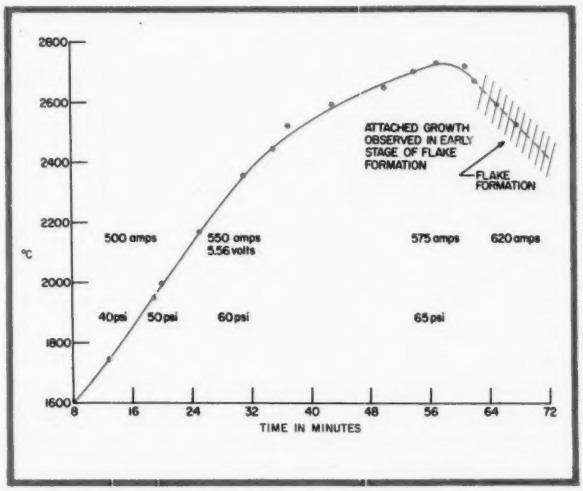


Figure 5

Since free silicon vapor is formed, leaving behind solid graphite, another source of carbon vapor is necessary. The sidewalls of the heater sleeve are thinned down at the reaction zone so that there will be a hotter region for evaporating carbon into the reaction zone.

With a suitable concentration of silicon and carbon vapors, a limited number of nucleation groups form. When these reach a certain critical size they tend to fall from the reaction zone. To keep these flakes in the reaction zone long enough for useful size, an upward flow of argon is maintained. The parameters of flow, pressure, temperature, temperature gradient, and temperature rise time have not all been investigated, so conditions for maximum size are not known.

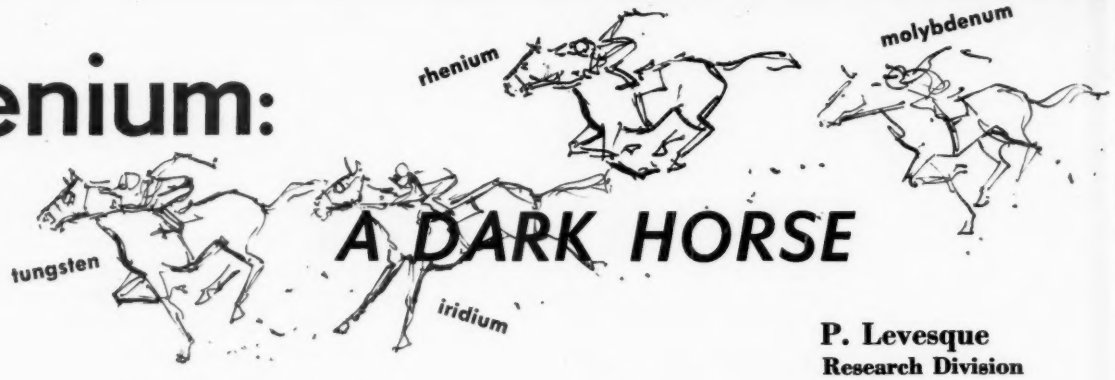
The effect of pressure has been observed in some preliminary experiments. At atmospheric pressure, the silicon vapors react with graphite surfaces throughout the interior of the apparatus, forming silicon carbide. At pressures about 160 psi the silicon vapors are confined to the reaction capsule. The mechanism is probably variation of the diffusion coefficient of the silicon in the argon. Pressures about 100 psi are adequate to let the vapors out of the capsule into the reaction zone without getting them all over the system.

The silicon carbide flakes that have been formed have been very regular and clear in color. Figure 6 shows an aggregate of the crystals just as they fell in the furnace. Triangles and hexagons, along with intermediate shapes, are dominant. Other objects are graphite and silicon spheres. The largest flakes are between 20 and 30 mils across and up to 0.5 mil in thickness. Occasionally some color can be observed in a flake, but as a rule they are perfectly clear and colorless.

Indication of purity has been inferred from observation of color and resistivity of the material. Pure silicon carbide is colorless and transparent, and has very high resistivity (above 10^6 ohm-cm). One polycrystalline specimen taken from this furnace measured 10^5 ohm-cm at room temperature. On the whole, this appears to be a very promising method of obtaining pure silicon carbide crystals. A doubling of the size of crystallites presently obtained would actually provide usable material for device fabrication. Experiments are now in process aimed at achieving this increase in crystallite size by enlarging the entire apparatus.

Figure 6

Rhenium: A DARK HORSE



P. Levesque
Research Division

UNFORTUNATELY, the lot of the electronic metallurgist is frequently a difficult one. He gets a headache from the device-making schemes of the semiconductor physicist, a chill from the missile designer (who is always squeezing the last ounce of performance from his material), and high blood pressure from the tube engineer (who insists of thinking of a cathode as a source of electrons rather than a source of troubles). Recently, however, the metallurgist has been wearing a roguish grin in anticipation of a new development which he believes will put him one-up on his vexatious friends, the electronics engineers.

In the race for acceptance as electronic construction materials, many metals and alloys are entered. In order to pick winners consistently the metallurgist must become a successful handicapper. He is currently excited about making a killing on a dark horse which has been bred by recent research both here and abroad. This dark horse which the metallurgist has been eyeing is a metal which was isolated from platinum and molybdenum ores by three German chemists around 1925. In honor of the German Rhineland, they named it rhenium.

In the United States the largest commercial source of rhenium is the flue dust resulting from the roasting of molybdenum sulfide ores. This yields about fourteen pounds of rhenium per ton of dust. The estimated concentration of the element in the earth's crust is about 0.004 part per million, corresponding to 74th in order of abundance, which indicates that rhenium is one of the rarest metals. Consequently, its price is very high. Rhenium of 99.95+ percent purity sells at prices ranging from $700 to over $2600 per pound, depending upon its form and size.

Rhenium has a melting point of 3180°C, second highest of all the elements (falling after tungsten). Its vapor pressure at 2800°C is about 10^{-3} millimeters of mercury. In the density race, rhenium just fails to show, with about 21 grams per cubic centimeter, not as good as iridium, osmium, and platinum. Rhenium has a specific electrical resistance of twenty-one microhm-centimeters at 20°C, about 3.6 times that of tungsten, and 110 microhm-centimeters at 2500°C, about 1.3 times that of tungsten. This allows the use of larger cross sections of rhenium for added ruggedness, and decreases the occurrence of filament hot spots, so often encountered with tungsten.

Rhenium has a thermionic function of 4.8 electron volts and a Richardson constant of fifty-two amperes per square centimeter per $°K^2$, as compared to tungsten's 4.6 electron volts and forty-five amperes per square centimeter per $°K^2$. Thermionic emission measurements on an activated Re-2.28% ThO_2 cathode indicate that, over certain temperature ranges, the emission from thoriated rhenium can be of the same order of magnitude as that from thoriated tungsten. The thoriated rhenium cathode activates at a lower temperature than the thoriated tungsten but begins to deactivate at temperatures which are still several hundred degrees below the lower activation limit of thoriated tungsten.

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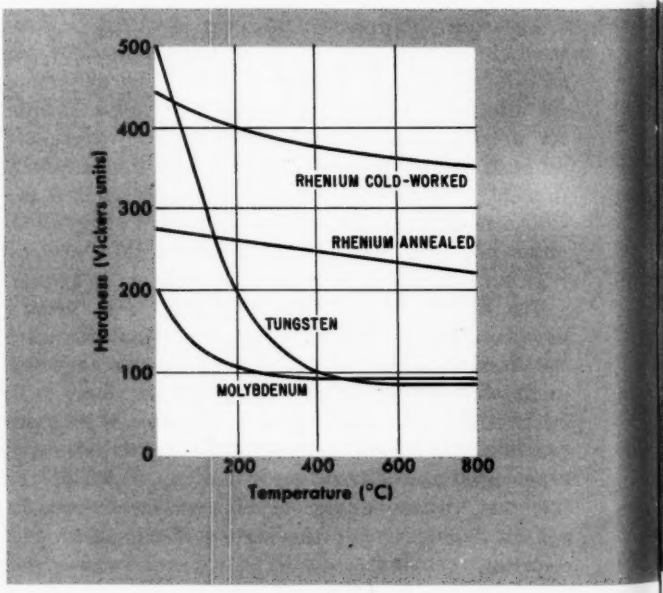

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Electron tube technologists have long known that tungsten filaments fail in commercial vacua even at temperatures below 2000°C because of the so-called water cycle reaction. The filament first reacts with water vapor to form tungsten oxide and atomic hydrogen. The volatile tungsten oxide then vaporizes from the filament and condenses on the cooler parts of the bulb. There it is reduced by atomic hydrogen to metallic tungsten with the re-formation of water. In a recent investigation at the Battelle Memorial Institute, rhenium appeared to be from 10 to 200 times as resistant as tungsten to the water cycle reaction.

The possibility that rhenium does not form a carbide was suggested as early as 1930. It was confirmed recently by a study of arc-melted rhenium-carbon alloy, which showed alpha-rhenium to be in equilibrium with graphite. A eutectic reaction occurs at 2480°C and 16.9 atomic percent carbon with alpha-rhenium containing about 11.7 atomic percent carbon at the eutectic temperature. This solubility of carbon in rhenium decreases rapidly to about 4.5 atomic percent at 2000°C. The absence of a carbide in the rhenium-carbon system is unique; other refractory metals such as tungsten, tantalum, molybdenum, and columbium form carbides and become excessively brittle after exposure to a carbonaceous atmosphere. This behavior of rhenium is probably associated with its relatively noble position in the periodic system, occupying the post between tungsten and osmium (a platinum-group metal).

Because boron-containing materials are potentially useful in electron tube technology, the search began to determine whether rhenium had as low a reactivity with boron as it had with carbon. At present, there is some preliminary evidence for the formation of a eutectic melting at about 2200°C.

Rhenium is also outstanding with respect to mechanical properties. It remains relatively strong and ductile following heating above its recrystallization temperature (about 1750°C), while tungsten and molybdenum become brittle to the point of having little mechanical usefulness. The very high ductility of rhenium, whether previously heated or not, at room temperature permits the fabrication of complicated shapes without fracturing and allows the part to withstand extreme mechanical shock and vibration after service at high temperatures. In addition, the elasticity modulus drops only twenty percent at 900°C from its room temperature value and elongation varies from a maximum 28 percent at room temperature to about 0.5 percent at 2000°C.

Rhenium additions to molybdenum and tungsten have produced alloys that are stronger, as well as more ductile, than either unalloyed tungsten or molybdenum. These beneficial effects, however, are lost at high rhenium content, where a brittle sigma phase is formed. This phase, when present in more than small quantities, causes a rapid decrease in ductility. However, the gain in ductility, fabricability, and strength imparted to tungsten and molybdenum at compositions ranging from 20 to 35 atomic percent rhenium should be of considerable interest in electron tube technology.

Tungsten-Rhenium Alloy Microstructure

Possible Applications of Rhenium

IN THE ELECTRON TUBE INDUSTRY

- Thoriated-rhenium cathode
- Rhenium-plated nickel cathode
- Rhenium-coated tungsten wire
- Rhenium and rhenium-refractory metals alloys for filaments, sleeves, and other structural materials
- Rhenium-titanium alloys for control grids and plates
- Powdered rhenium in cermet-type cathode

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- Thermocouple material for temperatures up to 2500°C
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- Evaporation filament in vapor-phase coating
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Rhenium: A DARK HORSE

P. Levesque
Research Division

UNFORTUNATELY, the lot of the electronic metallurgist is frequently a difficult one. He gets a headache from the device-making schemes of the semiconductor physicist, a chill from the missile designer (who is always squeezing the last ounce of performance from his material), and high blood pressure from the tube engineer (who insists of thinking of a cathode as a source of electrons rather than a source of troubles). Recently, however, the metallurgist has been wearing a roguish grin in anticipation of a new development which he believes will put him one-up on his vexatious friends, the electronics engineers.

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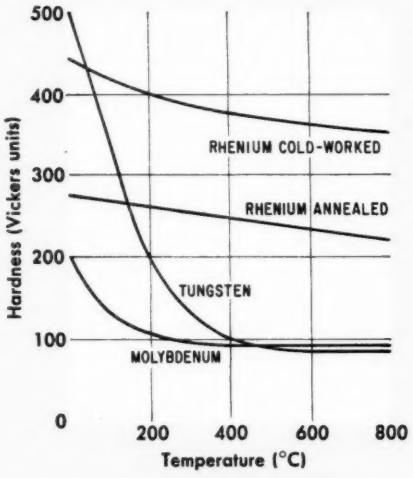

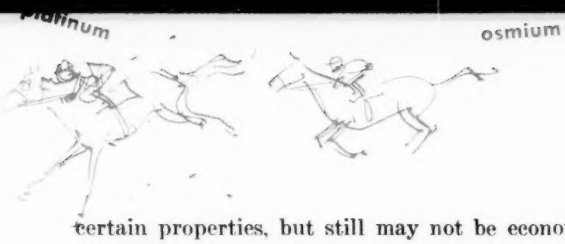

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And thus the fame of a recently uncovered dark horse has spread, a fame which will undoubtedly bring rhenium into more and more applications where performance is critical and quantity of material used is small. As rhenium is mated to such great performers as tungsten, molybdenum, nickel, tantalum, and columbium, even more exciting results can be predicted. High-temperature strength, high ductility without excessive work hardening, high melting point, extremely low vapor pressure, stability to water cycle reaction, stability in contact with carbon-bearing atmospheres, and ability to withstand mechanical and thermal shock will all become available in a fabulous racing stable of electronic materials.

Thermal Chemical, and Electrical Properties of Rhenium
Compared to those of Tungsten, Molybdenum, and Tantalum

		Rhenium	Tungsten	Molybdenum	Tantalum
Mass	Density (g/cc)	21.4	19.3	10.2	16.6
Thermal	Melting Point (°C)	3180	3410	2630	3000
	Vapor Pressure (mm Hg)				
	2000°C	$2x10^{-8}$	$1x10^{-9}$	$1x10^{-5}$	$1x10^{-8}$
	2500°C	$5x10^{-5}$	$4x10^{-5}$	$1x10^{-2}$	$2x10^{-5}$
	Specific Heat (cal / gr/°C) (0-100°C)	0.033	0.033	0.062	0.034
	Linear Coefficient of Expansion per °C ($x10^6$) (20-1000°C)	6.8	4.7	5.1	6.5
	Thermal Conductivity (cal/cm^2/cm/sec/°C) (0-100°C)	0.17	0.394	0.34	0.13
Chemical	Reaction with Carbon	none	800°C	800°C	1400°C
	Reaction with Nitrogen	none	1500°C	725°C	650°C
	Reaction with Oxygen	400°C	400°C	400°C	1000°C
Mechanical	Ultimate Tensile Strength (psi)				
	Annealed	170,000	192,000	85,000	75,000
	Cold-worked, 20°C	330,000	500,000	260,000	180,000
	Cold-worked, 1000°C	124,000	100,000	55,000	—
	Elongation (% in 2 in.)				
	Annealed	30	8	25	40
	Cold-worked	8	4	5	2
	Modulus of Elasticity (lb/in^2) x 10^6	67.5	52	42	27

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		Rhenium	Tungsten	Molybdenum	Tantalum
Electrical	Electrical Resistivity (μ ohm-cm)				
	20°C	21.1	5.5	5.7	13.5
	1000°C	76.0	31.0	30.0	52.0
	2000°C	105.0	62.0	60.0	86.0
	2500°C	110.0	83.0	78.2	102.0
	Temperature Coefficient of Electrical Resistivity per °C ($x10^3$) (0-2300°C)	2.1	4.6	4.6	3.8
Thermionic	Work function, eV	4.8	4.6	4.4	4.1
	Electron Emission amp/cm^2 (2600° K)	0.17	0.36	1.2	2.79
	Secondary Electron Emission Coefficient (δ max)	1.3	1.4	1.2	1.4
	Richardson Constant amp/cm^2/°K^2	52	45	60	37

Air Force TPPD's: Guidelines for Industry

In the technological contest currently being enacted on a world-wide basis, military planning of advanced weapons systems, countermeasures, and defense networks plays a crucial and pivotal role. These technically demanding areas are the focus for large scale expenditures of time and money by industrial and academic research centers, as well as by the Armed Forces' own development groups. The scientific advances that must still be made, and the numerous and incredibly complex technical problems that must be worked out in the interests of national defense will more and more require the closest cooperation between industry and the military.

The very first step in achieving such cooperation is, of course, adequate dissemination of information on long-range military objectives and the attendant research planning already under way. Understandably, however, the dictates of national security interpose several problems to free spreading of information. These communication problems have been the object of much study and many attempts at solution are currently being made by all the Services. For the present, the Air Force seems to have solved part of its problem through the use of Technical Program Planning Documents.

Established in mid-1955, the TPPD program arranges for the annual release to qualified companies of selected Air Force studies. These Documents cover a large number of broad functional areas such as communications, navigation and guidance, materials, propulsion, electronic techniques and advanced weapons. Qualification for this program rests primarily on a company's known integrity and demonstrated capability to participate advantageously, as well as on its possession of the appropriate security clearance. Participation establishes a "need-to-know" on a broad basis for access to the classified material of this program, thereby placing responsibility on the individual company to safeguard these Documents and see that full security control is maintained while they are in-plant.

For the Air Force these Documents serve to establish and delineate its future objectives. They also identify the technical problems that must find solution before the objectives can be transformed into operational realities. A valuable source of information for industry, the Documents provide the opportunity to relate the specific technical problems confronting Air Research and Development Command centers to a company's own R & D capabilities, and encourage the submission of useful proposals.

The advantages for both sides in this program are numerous. The Air Force broadens its contacts in the scientific community, while tapping the rich resources of industry for research. The program provides a means for the solution of problems that couldn't be tackled expeditiously within the Air Force's own facilities, as well as encouraging faster solution of all problems encompassed. One of the major advantages to the participating companies is the "need-to-know" that has been established. The additional information to which they have access provides a good indication of where future planning should be directed. More realistic research proposals are submitted, and, overall, industry is aided in its own development planning.

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RAYTHEON

SUBMINIATURE TUBES with RELIABILITY +

PROVED IN FLIGHT!

Available to U.S. Navy Specifications
Here are some of the features:

- Reduced vibration output after shock
- Increased clearance between elements
- Controlled operation time
- Tighter limits for important characteristics
- Greater uniformity
- Lower microphonics
- Better resistance to shock and fatigue
- Pulse emission test (where applicable)

YOUR COPY OF THIS NEW BOOKLET

will be mailed when you say the word. It pictures and describes the advanced manufacturing techniques developed by Raytheon and used in the production of these Subminiature Tubes with *Reliability Plus.*

RAYTHEON RELIABLE SUBMINIATURE TUBES For Guided Missile, Military and All Other Critical Applications
TYPICAL CHARACTERISTICS

TYPE	DESCRIPTION	Vibration Output* (maximum) mVac	Vibration Output** peak to peak mv	Heater Volts	Heater mA	Plate Volts	Plate mA	Cathode Bias Resistor ohms	Screen Volts	Screen mA	Amplification Factor	Mutual Conductance μmhos
CK5702WB	Video Amplifier, Pentode	50	240	6.3	200	120	7.5	200	120	2.6	—	5000
CK5703WB	High Frequency Triode	10	50	6.3	200	120	9.4	220	—	—	25.5	5000
CK5704WA	High Frequency Diode	—	25	6.3	150	Max. inverse peak = 460 volts; max. I_o = 10 mA						
CK5744WB	High Mu Triode	15	75	6.3	200	250	4.2	500	—	—	70	4000
CK5783WB	Voltage Reference	20	—	Operating voltage approximately 85 volts between 1.5 and 3.5 mA								
CK5784WB	RF Mixer Pentode	75	300	6.3	200	120	5.5	230	120	4.1	—	3200
CK5787WB	Voltage Regulator	20	—	Operating voltage approximately 98 volts between 5 and 25 mA								
CK6247WA	Low Microphonic	2.5	25	6.3	200	250	4.2	500	—	—	60	2650
CK6533WA	Low Microphonic Triode	1.0	15	6.3	200	120	0.9	1500	—	—	54	1750

Each type is electrically and mechanically interchangeable with earlier versions of the same basic type.
Developed under Navy sponsorship.

Bulb temperature ratings to 265°C.

*15g, 40 cps, fixed frequency
**15g, 30 to 1000 cps sweep

RAYTHEON

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